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THE THEORY OF PENTAQUARKS

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ABSTRACT

Is there a theory or good experimental evidence? Bj's question: Pentaquark is created by e^+e^- . $2q + q \rightarrow$ Baryon ; $2q + \bar{q} \rightarrow$ Triquark; $2q + \text{Triquark} \rightarrow$ Pentaquark Does it live long enough to be observable? Basic physics of constituent quarks and flavor antisymmetry. Report of Θ^+ violating flavor antisymmetry indicates need for two-cluster model.. Ball in Experimental Court - Some experiments see Θ^+ ; others don't. Possible production mechanisms present in some experiments, absent in others; e.g. via $N^*(2.3 \text{ GeV}) \rightarrow \Theta^+ + \bar{K}$?

1 QCD Guide to the search for exotics

1.1 Words of Guidance from Eugene Wigner's Wisdom

With a few free parameters I can fit an elephant.

With a few more I can make him wiggle his trunk

Wigner's response to questions about a particular theory he did not like was:

"I think this theory is wrong. But the old Bohr - Sommerfeld quantum theory was also wrong.. Could we have reached the right theory without it?"

1.2 BJ's question in 1986

In e^+e^- annihilation a created $q\bar{q}$ fragments into hadrons. $q + \bar{q} \rightarrow$ meson; $2q + q \rightarrow$ baryon. But $2q + \bar{q} \rightarrow$ Triquark and $2q + \text{Triquark} \rightarrow$ Pentaquark..

BJ asked whether quark model says such state is bound or lives long enough to be observable as hadron resonance. Listening to BJ usually pays off.

1.3 Crucial role of color-magnetic interaction

1. QCD motivated models ¹⁾ show same color-electric interaction for large multiquark states and separated hadrons and no binding. Only short-range color-magnetic interaction produces binding.
2. Jaffe ²⁾ extended DGG model ¹⁾ with one-gluon-exchange color factor to multiquark sector in a single cluster or bag model, defined $(\bar{q}q)_8$ and $(qq)_6$ interactions and explained why lowlying exotics not observed
3. Hyperfine interaction suggested search for H dibaryon ²⁾ $uuddss$ and anticharmed strange pentaquark ³⁾ $(\bar{c}uuds)$ (1987)

1.4 Flavor antisymmetry principle - removes leading exotics

The Pauli principle requires flavor-symmetric quark pairs to be antisymmetric in color and spin at short distances. Thus the short-range color-magnetic interaction is always repulsive between flavor-symmetric pairs. Best candidates for multiquark binding have minimum number of same-flavor pairs

1. Nucleon has only one same-flavor pair; $\Delta^{++}(uuu)$ has three.
2. Extra two same-flavor pairs costs 300 MeV .
3. Deuteron separates six same-flavor pairs into two nucleons
Only two same-flavor pairs feel short range repulsion.
4. $H(uuddss)$ has three same-flavor pairs. Optimum for light quark dibaryon

5. The $(uuds\bar{c})$ pentaquark has only one same-flavor pair
6. Θ^+ ($uudd\bar{s}$) has two same-flavor pairs, more than $(uuds\bar{c})$.

Quark model calculations told experimenters "Look for $\bar{c}(uuds)$ not Θ^+ .

Ashery's E791 search for $\bar{c}uuds$ found events ⁴⁾; not convincing enough.

Better searches for this pentaquark are needed; e.g. searches with good vertex detectors and good particle ID ³⁾...

Any proton emitted from secondary vertex is interesting. One gold-plated event not a known baryon is enough; No statistical analysis needed.

2 The 1966 basic physics of hadron spectroscopy - Sakharov-Zeldovich, Nambu and beyond

2.1 Sakharov-Zeldovich (1966)

Sakharov and Zeldovich noted that the Λ and Σ are made of same quarks and asked why their masses are different. Their answer was that a unified two-body hyperfine interaction not only answers this question but led to a unified mass formula for both meson and baryon ground states mesons and baryon masses and showed that all are made of same quarks ⁵⁾

$$M = \sum_i m_i + \sum_{i>j} \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i \cdot m_j} \cdot v_{ij}^{hyp} \quad (1)$$

Using (1) Sakharov and Zeldovich noted that both the mass difference $m_s - m_u$ between strange and nonstrange quarks and the flavor dependence of their hyperfine splittings (later related ¹⁾ to the mass ratio m_s/m_u) have the same values when calculated from baryon masses and meson masses ⁵⁾, along with the comment that the masses are of course effective masses ⁶⁾:

$$\begin{aligned} \langle m_s - m_u \rangle_{Bar} &= M_\Lambda - M_N = 177 \text{ MeV} \\ \langle m_s - m_u \rangle_{mes} &= \frac{3(M_{K^*} - M_\rho) + M_K - M_\pi}{4} = 180 \text{ MeV} \end{aligned} \quad (2)$$

$$\begin{aligned} \langle m_s - m_u \rangle_{Bar} &= \frac{M_N + M_\Delta}{6} \cdot \left(\frac{M_\Delta - M_N}{M_{\Sigma^*} - M_\Sigma} - 1 \right) = 190 \text{ MeV} \\ \langle m_s - m_u \rangle_{mes} &= \frac{3M_\rho + M_\pi}{8} \cdot \left(\frac{M_\rho - M_\pi}{M_{K^*} - M_K} - 1 \right) = 178 \text{ MeV}, \end{aligned} \quad (3)$$

The same value $\pm 3\%$ for $m_s - m_u$ is obtained from four independent calculations. The same approach for $m_b - m_c$ gives

$$\begin{aligned}\langle m_b - m_c \rangle_{Bar} &= M(\Lambda_b) - M(\Lambda_c) = 3341 \text{ MeV} \\ \langle m_b - m_c \rangle_{mes} &= \frac{3(M_{B^*} - M_{D^*}) + M_B - M_D}{4} = 3339 \text{ MeV}\end{aligned}\quad (4)$$

The same value $\pm 2.5\%$ for the ratio $\frac{m_s}{m_u}$ is obtained from meson and baryon masses.

$$\left(\frac{m_s}{m_u}\right) = \frac{M_\Delta - M_N}{M_{\Sigma^*} - M_\Sigma} = 1.53 = \frac{M_\rho - M_\pi}{M_{K^*} - M_K} = 1.61 \quad (5)$$

DeRujula, Georgi and Glashow ¹⁾ in 1975 used QCD arguments to relate hyperfine splittings to quark masses and baryon magnetic moments. This led to remarkable agreement with experiment including three magnetic moment predictions with no free parameters

$$\begin{aligned}\mu_\Lambda &= -0.61 \text{ n.m.} = -\frac{\mu_p}{3} \cdot \frac{m_u}{m_s} = -\frac{\mu_p}{3} \frac{M_{\Sigma^*} - M_\Sigma}{M_\Delta - M_N} = -0.61 \text{ n.m.} \\ \mu_p + \mu_n &= 0.88 \text{ n.m.} = \frac{M_p}{3m_u} = \frac{2M_p}{M_N + M_\Delta} = 0.865 \text{ n.m.} \\ -1.46 &= \frac{\mu_p}{\mu_n} = -\frac{3}{2},\end{aligned}\quad (6)$$

2.2 Two Hadron Spectrum puzzles -Why qqq and $q\bar{q}$?

1. The Meson-Baryon Puzzle - The qq and $\bar{q}q$ forces must be peculiarly related to bind both mesons and baryons. It cannot be a vector interaction giving equal and opposite forces, nor a scalar or tensor giving equal attractions for both.
2. Exotics Puzzle - No low-lying hadrons with exotic quantum numbers have been observed; e.g. no $\pi^+\pi^+$ or K^+N bound states.

Nambu solved both puzzles ⁷⁾ in 1966 by introducing the color degree of freedom and a two-body interaction from a non-abelian gauge theory with the color-factor of one-gluon exchange. This both related mesons and baryons and eliminated exotics.

A unified treatment of qq and $\bar{q}q$ interactions binds both mesons and baryons with the same forces. Only qqq and $q\bar{q}$ are stable in any single-cluster model with color space factorization. Any color singlet cluster that can break up into two color singlet clusters loses no color electric energy and gains kinetic energy. The Nambu color factor does not imply dynamics of one-gluon exchange. Higher order diagrams can have same color factor

Looking beyond bag or single-cluster models for possible molecular bound states Lipkin(1972) showed that the color-electric potential energy could be lowered in potential models by introducing color-space correlations; e.g, $q\bar{q}q\bar{q}$ at corners of a square, but not enough to compensate for the kinetic energy ⁸⁾

2.3 Important systematics in the experimental spectrum

A large spin-dependent interaction ≈ 300 MeV but a very weak interaction ≈ 2 MeV binding normal hadrons.

$$M(\Delta) - M(N) \approx 300 MeV \gg M(n) + M(p) - M(d) \approx 2 MeV \quad (7)$$

2.4 Conclusions from basics

The low-lying hadron spectrum is described by a linear effective mass term and a hyperfine interaction with a one-gluon exchange color factor.

The $(\bar{q}q)$ and (qqq) states behave like neutral atoms with a strong color electric field inside hadrons and none outside. No molecular bound states arise in the simplest cases. A strong spin-dependent interaction is crucial to understanding the spectrum

Only color singlet and 3^* color factors arise in $(\bar{q}q)$ and (qqq) . The low-lying hadron spectrum provides no direct experimental information on $(\bar{q}q)_8$ and $(qq)_6$ interactions needed for multiquark exotic configurations.

2.5 What can QED teach us about QCD?

QCD is a Great Theory, but nobody knows how to connect it with experiment or which approximations are good. We need to construct instructive simplified models. I often recall the response by Yoshio Yamaguchi at a seminar at the Weizmann Institute in 1960 when asked if there had been any thought at CERN about a possible breakdown of QED at small distances: “No. . . Many calculations. No thought.”

What can we learn from QED; a Great Theory that everyone knows how to connect with experiment? We know how isolated free electrons behave and carry currents. But nobody could explain the fractional Hall effect until Robert Laughlin told us the Hall Current is not carried by single electrons! It is carried by quasiparticles related to electrons by a complicated transformation.

Nobody has ever seen an isolated free quark. Current quark fields appear in the Standard Model Lagrangian. But experiments tell us that baryons are qqq and mesons are $q\bar{q}$ and these are not the quarks that appear in the QCD Lagrangian.

Nobody knows what these quarks are. Are they complicated quasiparticles related to current quarks by a complicated transformation?. Is Hadron Spectroscopy Waiting for Laughlin? Does QCD need another Laughlin to tell us what constituent quarks are?

3 The Θ^+ was reported! A Two-cluster Model?

3.1 Following Wigner's Guidance to Understand QCD and the Pentaquark

One good wrong model that stays away from free parameters and may teach us something: a two-cluster P -wave (ud) diquark- $(ud\bar{s})$ triquark model ^{9, 10} for the Θ^+ that separates uu and dd pairs and eliminates their short range repulsive interaction... Its hidden-strangeness N^* partner keeps the same triquark with the (us) and (ds) $SU(3)$ partners of the (ud) diquark. Its mass is roughly ¹¹

$$M[N^*(1775)] \approx M(\Theta^+) + M(\Lambda) - M(N) + \frac{3}{4} \cdot [M(\Sigma) - M(\Lambda)] \approx 1775 \text{ MeV} \quad (8)$$

3.2 The skyrmion model

Experimental search motivated by another wrong model. Skyrmion model has no simple connection with quarks except by another wrong model. The $1/N_c$ expansion invented ¹² pre-QCD to explain absence of free quarks.

The binding Energy of $q\bar{q}$ pairs into mesons $E_M \approx g^2 N_c$.

At large N_c the cross section for meson-meson scattering breaking up a meson into its constituent quarks is

$$\sigma[MM \rightarrow M + q + \bar{q}] \approx g^2 \frac{E_M}{N_c} \approx 0 \quad (9)$$

But $\frac{1}{N_c} = \frac{1}{3}$; $\frac{\pi}{N_c} \approx 1$ This is NOT A SMALL PARAMETER!

4 Experimental contradictions about the Θ^+

Some experiments ^{13, 14, 15, 16)} see the Θ^+ ; others ^{17, 18)} definitely do not. Further analysis is needed to check presence of specific production mechanisms in experiments that see it and their absence in those that do not ¹⁹⁾. No theoretical model addresses this question. Comprehensive review ²⁰⁾ analyzes different models..

4.1 Production via decay of a cryptoexotic $N^*(2400)$

The reported ^{14, 21, 22, 23)} $N^*(2400)$ can be the D -wave excitation of the $N^*(1775)$.with a (ds) diquark in a D -wave with the same $ud\bar{s}$ triquark. Its dominant decays would be $N^*(2400) \rightarrow K^-\Theta^+$ via the diquark transition $ds \rightarrow ud + K^-$.and $N^*(2400) \rightarrow \pi^- N^*(1775)^+ \rightarrow \pi^- \Lambda K^+$ via $ds \rightarrow us + \pi^-$.

Decays like ΛK and ΣK would be suppressed by the centrifugal barrier forbidding a quark in the triquark from joining the diquark.

Some experimental checks of this mechanism are:

1. Experiments which see the Θ^+ and have sufficient energy for producing the $N^*(2400)$ should look for an accompanying K^- or K_s and examine the mass spectrum of the $K^-\Theta^+$ and $K_s\Theta^+$ systems.
2. Experiments should look for $N^*(2400) \rightarrow \pi^- N^*(1775)^+ \rightarrow \pi^- \Lambda K^+$.
3. Experiments searching for the Θ^+ should check possible production of a $K^-\Theta^+$ or $K_s\Theta^+$ resonance in the 2.4 GeV region. B -decay modes suggested for pentaquark searches ^{24, 25)} would not produce this 2.4 GeV N^* . Similar considerations should be applied to searches in e^+e^- and $\gamma\gamma$ like those proposed in Ref. ²⁶⁾.
4. The other $N^*(2400)$ decay modes.; e.g. $K\Lambda$, $K\Sigma$, $K\Sigma^*$, ϕN , are suppressed by the centrifugal barrier in the D-wave diquark-triquark model but may be appreciable.. Finding them would give further evidence for this model for pentaquark production. The relative branching ratios would also provide information about the structure of th $N^*(2400)$.

4.2 Angular distribution tests for production mechanisms

1. The angular distribution of the kaon emitted with the Θ^+ in $\gamma p \rightarrow \bar{K}^0 \Theta^+$ ²⁷⁾ carries interesting information. Production from a cryptoexotic N^* , gives no forward-backward kaon asymmetry. Meson exchange gives forward peaking. Baryon exchange gives backward peaking, produces the Θ^+ equally by photons on protons and neutrons. and the same baryon exchange should be seen ²⁸⁾ in $\gamma n \rightarrow K^- \Theta^+$..
2. The more complicated angular distributions in $\gamma p \rightarrow \pi^+ K^- K^+ n$ ¹⁴⁾ may still carry interesting information.

All the above discussion for $\gamma p \rightarrow \bar{K}^0 \Theta^+$ applies to the angular distribution of a \bar{K}^* . in $\gamma p \rightarrow \bar{K}^{*0} \Theta^+ \rightarrow \pi^+ K^- \Theta^+$. Models ²⁸⁾ with a suppressed $NK\Theta^+$ coupling relative to $NK^*\Theta^+$ predict stronger Θ^+ production with a backward K^* than with a backward kaon.. In $\gamma p \rightarrow \pi^+ N^* \rightarrow \pi^+ \Theta^+ K^-$ ¹⁴⁾, the pion goes forward and everything else is in the target fragmentation region. ²¹⁾..

4.3 Other experimental considerations

1. Search for exotic positive-strangeness baryon exchange in normal nonexotic reactions. The baryon exchange diagram ²⁷⁾ for Θ^+ photoproduction with an outgoing kaon is simply related to backward $K^- p$ charge-exchange ²⁸⁾. The lower $KN\Theta^+$ vertices are the same; the upper vertex is also $KN\Theta^+$ for $K^- p$ charge-exchange but $\gamma\Theta^+\Theta^+$ for Θ^+ photoproduction. If this diagram contributes appreciably to Θ^+ photoproduction, the contribution of the $KN\Theta^+$ vertex is appreciable and should also contribute appreciably to backward $K^- p$ charge-exchange. Some previously ignored backward $K^- p$ charge-exchange data may be available.
2. The baryon and \bar{s} constituents of the Θ^+ are already initially present in low-energy photoproduction experiments in the target baryon and the \bar{s} component of the photon. In experiments where baryon number and strangeness must be created from gluons, the cost of baryon antibaryon and $s\bar{s}$ production by gluons must be used to normalize the production cross section in comparison with the photoproduction cross sections; e.g. from baryon-antibaryon production and $s\bar{s}$ production data in the same experiment that does not see the Θ^+ .

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